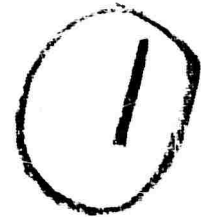


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## FINAL TECHNICAL REPORT

on

## DIRECT ENERGY CONVERSION SYSTEMS

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Prepared for

Advanced Research Project Agency

Director of Material Sciences

Submitted by

Robert H. Eustis, Principal Investigator

For the period

1 November 1961 - 30 September 1965

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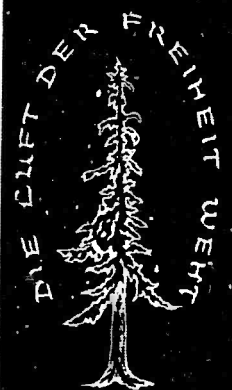
Contract Expiration Date:

30 September 1965

29 October 1965

Department of Mechanical Engineering

STANFORD UNIVERSITY ■ STANFORD, CALIFORNIA



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Final Technical Report  
on  
DIRECT ENERGY CONVERSION SYSTEMS

Prepared for

Advanced Research Projects Agency  
(ARPA Order No. 246, Amendment No. 6,  
Contract AF 49(638)-1123)

Submitted by  
Robert H. Eustis, Principal Investigator  
Mechanical Engineering Department  
Stanford University

29 October 1965

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## ABSTRACT

The present report gives a brief summary of the research conducted under contract AF 49(638)-1123. Details of the work are reported in earlier Quarterly and Semi-annual Reports. The scope of this program on "Direct Energy Conversion Systems" included magnetogasdynamic, electrochemical, and thermoelectric research programs.

In addition to a summary of the research work, this report shows that 22 technical papers and ten theses were generated by 26 students and by faculty who were supported by the contract. Many programs initiated under this contract are continuing with other support.

## 1.0 INTRODUCTION

The present report is the final report written under contract AF 49(638)-1123 which was supported by the Advanced Research Projects Agency and administered by the Solid State Sciences Division, Directorate of Physical Sciences, Air Force Office of Scientific Research. The research effort included studies of magnetogasdynamics, fuel cell, and thermoelectric energy conversion and included faculty and students from the Departments of Mechanical Engineering, Aeronautical Engineering, Materials Science, Chemical Engineering, and Chemistry.

The faculty and senior research personnel responsible in the several areas of research are listed below:

### Magneto Gas Dynamic Energy Conversion

Continuous Flow Facility - Professor C. H. Kruger  
Professor M. Mitchner  
Professor R. H. Eustis  
Mr. K. G. Reseck  
Mr. J. R. McLean  
Mr. K. H. Powell

Shock Tube Facility - Professor D. Bershader

### Electrochemical Energy Conversion

Kinetic Studies - Professor D. M. Mason  
Dr. P. Van Rysselberghe  
Dr. P. Stonehart

Chemisorption Studies - Professor E. Hutchinson

### Thermoelectric Energy Conversion

Basic Materials Research - Professor D. A. Stevenson

Property Measurement at  
Elevated Temperatures - Professor R. H. Eustis

Transient Performance of  
Thermoelectric Generators - Professor R. F. Eustis

A summary of the work undertaken on this program is given in this report. Details of the work are reported in the many Quarterly Technical Reports and their Supplements. A list of published papers, theses, and students who have received major support from the present contract are listed at the end of each major section of this report.

## 2.0 MAGNETOGASDYNAMICS

### 2.1 MGD Continuous Flow Facility

A combustion MGD test facility was designed, built, and operated as a generator and as a facility for fluid flow and heat transfer studies. When operating as a generator the test section contains thirteen pairs of electrodes and is 1-1/4 x 4 x 20 inches in width, height, and length, respectively. Potassium-hydroxide seeded alcohol burned with oxygen and nitrogen provides a plasma with flow rates up to 0.8 pound per second and temperatures to 3100°K. A magnet is available for producing a field of 2.7 tesla over the test section volume.

2.1.1 Generator Experiments - Many generator experiments were made with test durations up to one and one-half hours. Long term transient phenomena were recorded which had not been previously observed. The effect of hot and cold electrodes, seeding rate, gas temperature, velocity, and mode of operation were investigated. Operation as a continuous and segmented generator showed little difference in performance whereas connection in the Hall mode gave reduced performance. Two-dimensional effects were shown to be important.

2.1.2 Fluid Friction - For the first time in a gaseous plasma, Hartmann flow with associated pressure drop was measured. Inclusion of compressibility and temperature gradients will make these results useful in the design of

large MGD generators. This work is continuing.

An analysis of the turbulent MHD boundary layer was made using the velocity profiles deduced by Harris from earlier work by Hartmann and Lazarus. This provided a substantial improvement in calculation procedure over the usual method of assuming a one-seventh power velocity profile.

A mixing length theory was developed to account for the turbulence damping effect of the magnetic field on turbulent MHD flows. The theory agrees well with the meager experimental data available.

2.1.3 Heat Transfer - Experiments have been made to investigate the heat transfer to a wall with a step temperature change which is a model for cooled electrodes. This work is continuing and will be valuable for much high temperature gas flow work. Heat flux and stagnation pressure measurements in the MHD boundary layer were initiated under this contract and are continuing.

2.1.4 Physics - An analysis of the rapid expansion of an ionized gas through a nozzle has shown that the mechanism leading to an elevated electron temperature proposed by McNab and Lindley is not valid. A corrected analysis and preliminary experiments suggest that the electron temperature may be greater than the gas temperature during rapid expansion of seeded combustion gas and more significantly greater in argon expansion.

The calculation of the electron conductivity of a multi-component partially-ionized gas using the well-known method of Chapman-Enskog, leads to the inversion of a matrix of order  $\nu \times \xi$ . Here  $\nu$  denotes the number of species and  $\xi$  the order of approximation. By exploiting the fact of the small electron mass, it has been shown that the calculation may be simplified to the inversion of a matrix of order  $\xi$ , independent of the number of species. Using the Chapman-Enskog calculation in the third approximation as a standard for comparison, the accuracy of several mixture rules for the



calculation of the electrical conductivity of partially-ionized gases have been assessed.

Closed-form expressions for the transverse electrical conductivities for a fully ionized gas in a magnetic field have been derived in the third Chapman-Enskog approximation. A new and more accurate mixture rule has been developed for the transverse electrical conductivities of partially ionized gases in a magnetic field.

The Boltzmann equation for the free-electron distribution function in a partially-ionized nonequipartition plasma has been formulated using the Fokker-Planck operator for electron-electron collisions and an expansion in spherical harmonics. Consideration has been given to elastic electron-neutral, electron-ion, and electron-electron collisions and inelastic, superelastic, and three-body and two-body ionization and recombination collisions. Based on this formulation, an order-of-magnitude analysis of the various regimes of electron temperature and degree of ionization has been performed. The equations have been integrated numerically for the case of elastic collisions. The transition of the electron distribution function from the weakly-ionized form to an elevated temperature Maxwellian has been demonstrated in accord with the order-of-magnitude analysis. The nonequipartition electrical conductivity has been obtained for an arbitrary degree of ionization.

The following papers and theses have been published or are now in preparation:

#### Papers

1. K. G. Reseck, C. H. Kruger, R. H. Eustis, "Design and Performance of the Stanford Combustion MHD Generator", Proceedings of the Sixth Symposium on Engineering Aspects of MHD, University of Pittsburgh, Pittsburgh, Pennsylvania, April 21-22, 1965.

2. D. A. Oliver, R. H. Eustis, "Calculation of Idealized MGD Generator Performance with Non-Equilibrium Electron Heating", Proceedings of the ASME International Conference on Energetics, University of Rochester, August 18-20, 1965.
3. C. H. Kruger and O. K. Sonju, "On the Turbulent MHD Boundary Layer", Proceedings of the 1964 Heat Transfer and Fluid Mechanics Institute. Proceedings of the Sixth Symposium on Engineering Aspects of MHD, University of Pittsburgh, April 21-22, 1965.
4. C. H. Kruger and J. R. Viegas, "Influence of the Ramsauer Effect on Nonequilibrium Electron Temperatures", The Physics of Fluids, Volume 7, No. 11, November 1964.
5. S. Schweitzer and M. Mitchner, "Electrical Conductivity of Partially Ionized Gases", Proceedings of the Sixth Symposium on Engineering Aspects of MHD, University of Pittsburgh, April 21-22, 1965.
6. O. K. Sonju, and C. H. Kruger, "Experiments on Turbulent Hartmann Flow in Plasmas", American Physical Society, Fluid Dynamics Division, 1965.
7. S. Schweitzer and M. Mitchner, "Electrical Conductivity of Partially Ionized Gases", Submitted to AIAA Journal, August, 1965.
8. S. Schweitzer and M. Mitchner, "Transverse Electrical Conductivities in a Fully Ionized Plasma", Note to be submitted to Physics of Fluids.
9. S. Schweitzer and M. Mitchner, "Electrical Conductivities of Partially Ionized Gases in a Magnetic Field", Paper to be submitted to AIAA Journal.
10. F. H. Morse, M. Mitchner and C. H. Kruger, "On a Proposed Mechanism for Obtaining Elevated Electron Temperatures", Note submitted to Physics of Fluids.

### Theses

1. Peter C. Steel, Engineer, Mechanical Engineering, "An Analysis of the Performance of a Magnetogasdynamic Power Generator", June 1964.
2. Samuel Schweitzer, Ph.D., Mechanical Engineering, "Transport Properties of an Ionized Gas Mixture", June, 1966.
3. John R. Viegas, Ph.D., Mechanical Engineering, "Electron Distribution Function in a Non-equilibrium Plasma" June, 1966.
4. Karl G. Reseck, Ph.D., Mechanical Engineering, "Performance Characteristics of an Operational Combustion Driven MGD Power Generator", June, 1966.

Students who have received support from the present contract are the following:

O. Biblarz, Ph.D., 1966  
T-M. Fu, transferred to University of Washington  
G. Hohnstreiter, Ph.D., 1966  
R. Kessler, Ph.D., 1966  
H. McKee, Ph.D., 1966  
J. G. Olin, Ph.D., 1966  
D. Oliver, Ph.D., 1966  
M. H. Reid, transferred to University of California  
K. G. Reseck, Ph.D., 1965  
S. Schweitzer, Ph.D. 1965  
J. Shaw, M.S., 1964; Ph.D.  
O. K. Sonju, Ph.D., 1965  
P. C. Steel, Engineers, 1964  
J. R. Viegas, Ph.D., 1965

## 2.2 MGD Shock Tube Facility

The function of the shock tube work was to perform quantitative experiments with shock-heated plasmas which would augment our understanding of their physical properties and dynamic behavior. The program required design, construction and calibration of a suitable shock tube facility, together with associated instrumentation, which would cover and extend somewhat the range of parameters having importance for the performance of the MGD power generation research device. Also included in the program were parallel analytical studies concerned with the ionization kinetics and with the transport properties of dense, moderate-temperature plasmas.

Performance of the shock-tube, an extruded aluminum tube of square cross section, driven by hydrogen-oxygen combustion, has generally satisfied predictions. Initial operation took place in mid-autumn 1962 and the facility has seen continuing use since that time in a series of research investigations. Results of experimental and analytical investigations include:

- (1) Calibration of shock tube performance over a wide range of operating conditions;
- (2) Evaluation of the overall precision and limitations on the use of optical interferometry to measure electron density in the dense plasma range,  $10^{15} - 10^{18}/\text{cm}^3$ ;
- (3) Determination of the detailed physical model which correctly describes thermal equilibration processes in a shock-heated, ionized monatomic gas;
- (4) Calculation of the high temperature transport properties of monatomic gases, using the higher approximations of the Chapman-Enskog formalism.

Follow-on programs now under way and supported by a NASA grant include study of

- (1) Recombination processes in a flowing plasma cooled by a stationary expansion wave;
- (2) Radiation cooling rate of a quasi-equilibrium plasma flow;
- (3) Measurement of electron distribution and transport properties in plasma boundary layers.

The following papers and theses have been published or are now in preparation:

#### Papers

1. H. Wong and D. Bershader, "Interferometric Study of Thermal Equilibration of a Shock-Heated Plasma", J. Fluid Mechanics. To be published.
2. R. S. de Voto, "Argon Plasma Transport Properties", Physics of Fluids", to be published.
3. H. Wong, "Interferometric Study of Thermal Equilibration of a Shock-Heated Plasma", AIAA Paper 64-376, June 1964.
4. H. Wong and D. Bershader, "Thermal Equilibration Behind an Ionizing Shock Wave", Bull. Am. Phys. Soc., Series II, Vol. 10, No. 2, p. 268, Feb. 1965.
5. H. Wong and K. Horn, "Radiative Cooling Behind Strong Shock Waves", Proc. of the Fifth Shock Tube Symposium, N. O. L., White Oak, Maryland, April, 1965 (in press).
6. R. S. de Voto, "Transport Properties of Partially Ionized Monatomic Gases", AIAA Paper 65-540, San Francisco, June 1965.

### Theses

1. Howard Wong, Ph.D., Aeronautics and Astronautics, June 1964, "Interferometric Study of Thermal Equilibration of a Shock Heated Plasma".
2. Ralph Stephen de Voto, Ph.D., Aeronautics and Astronautics, June 1965, "Transport Properties of Partially Ionized Monatomic Gases".

The following theses programs were independently supported but made use of the shock tube facility and dealt with the closely related subjects:

Charles Elliott, Engineers Degree, Aeronautics and Astronautics, August 1964, "Interferometric Study of the Shock Layer of a Cylinder Immersed in a Flowing Plasma".

William Y. Cole, Engineers Degree, August, 1964, "Measurement of Electron Density in a Shock-Heated Plasma and Comparison with the Saha Equation".

Students who have received support from the contract are the following:

- R. S. de Voto, Ph.D., 1965
- H. Wong, Ph.D., 1964
- K. Horn, Ph.D., 1966
- P. E. Oettinger, Ph.D., 1966

### 3.0 ELECTROCHEMICAL ENERGY CONVERSION

#### 3.1 Kinetic Studies

##### 3.1.1 Translating Electrode

A translating electrode device has been developed for the study of electrode processes in which mass transport plays a significant role. Cylindrically shaped electrodes are mounted in the leading edge of a larger lucite cylinder which, in turn, is mounted on the end of a hollow L-shaped shaft. When the shaft is rotated at a constant angular velocity in an electrolytic solution, a boundary layer and therefore a diffusion layer of constant thickness is established over the entire electrode surface. The solution of the laminar boundary layer equations and the equation for convective motion enable the determination of the concentration of diffusing species at the solid-liquid interface as a function of the current density and the rotational speed. Analytical results are presented for diffusion-rate control, intermediate kinetics and diffusion-rate control, and reaction rate control.

The translating electrode apparatus was tested by studying the oxidation of hydrogen on platinized, smooth polycrystalline, and single crystal platinum electrodes in dilute HCl at potentials between zero and 1 volt.

The predicted linear dependency of current density on the square root of the rotational speed was verified for Reynolds numbers between 344 and  $6.05 \times 10^4$  using platinized platinum electrodes. Diffusion coefficients for hydrogen in 0.5 N HCl were calculated using diffusion limited current densities.

Bright polycrystalline and single crystal platinum electrodes were found to behave in a manner strikingly different from the behavior of platinized platinum. Current densities were essentially independent of rotational speed between about 0 - 0.4 volts. A sharp rise in catalytic activity starting at about 0.4 volts caused the current to

increase rapidly. The latter reached a peak at 0.62 volts and dropped off with further increases in potential. Upon depolarization from 1 volt the catalytic activity remained at a high level down to potentials of about 0.5 volts. An explanation of this behavior is presented based on recent information regarding platinum oxide film formation. A kinetic analysis of the peak currents gives strong evidence that the slow step in the hydrogen ionization reaction is either the charge step itself or surface diffusion to sites at which the charging step takes place.

### 3.1.2 Oxidation of Methanol

The anodic oxidation of methanol on single-crystal and polycrystalline platinum electrodes in acid solution was investigated using potentiostatic sweeping. The effect of doping the platinum electrodes with small concentrations of other metals was studied in an effort to determine factors responsible for the electrocatalytic activity of platinum for this reaction, with a view to discovering ways to enhance the electrocatalytic activity of electrodes for possible fuel cell use. Formaldehyde and formic acid were included in the study because of their probable involvement in the mechanism of methanol oxidation. The voltammetric behavior of platinum in an electrolyte not containing methanol or other organic material was also investigated, and its electrochemical properties were correlated with those of anodic methanol oxidation over the potential range zero to one volt against the saturated calomel electrode, (SCE).

One normal perchloric acid was the supporting electrolyte in all of the runs. Potential sweep rates from 3.3 to 2000 mv/min. were used, and temperatures ranged from 20 to 60°C. Cylindrical electrodes with an apparent area of one square centimeter were used. The apparatus consisted entirely of pyrex, quartz, Teflon and platinum to prevent electrolyte contamination, and an atmosphere of pure argon was maintained



in the cell. The anode potential was controlled by an externally programmed electronic potentiostat, and the polarization characteristics were recorded on an X-Y recorder. A logarithmic converter was used in conjunction with the recorder to record Tafel plots directly.

From the voltammetric curves of platinum in the electrolyte in the absence of methanol and from the literature on the formation of surface platinum oxides, the conclusion has been drawn that the methanol oxidation reaction is controlled by the oxidation state of the platinum electrode surface. A platinum oxide in the region 0.3 - 0.6 volt (vs. SCE) possesses electrocatalytic activity for methanol oxidation, whereas the oxide in the range 0.6 - 0.9 volt has considerably less electrocatalytic activity for this reaction. No conclusions have been drawn about the structure of these oxides. The significant point is that their formation requires a redox reaction at the electrode surface, and thus, something more than simple adsorption is involved.

The potential sweep rate determines to a great extent the shape of the current - voltage curve, the Tafel slope and the apparent exchange current. The slow rates of formation and removal of the two platinum oxides account for this behavior.

The lack of significant effect in the doping runs and in similar experiments with alloy electrodes reported in the literature is explicable on the basis that a surface oxide, rather than metallic platinum, is the catalyst for the methanol oxidation reaction.

Electrodes doped with iron, nickel, manganese, copper and zinc did not exhibit electrochemical activity that was significantly different from undoped platinum. Of two cobalt-doped electrodes, one behaved the same as platinum, but the other gave peak currents an order of magnitude greater. However, a comparison of coulometric charging curves in 1N HClO<sub>4</sub> with charging curves for a platinized electrode with

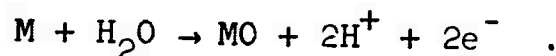
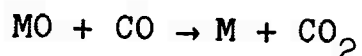
similar electrochemical properties indicated that the true surface areas of the two electrodes were the same. The probable explanation is that leaching of the cobalt produced a roughened surface, and that the high roughness factor accounted for the increase in electrochemical activity.

No differences in electrochemical behavior for the anodic oxidation of methanol were noted for single-crystal platinum as compared with polycrystalline platinum. The single crystals were of random orientation and no attempt was made to select a particular crystal face in determining the polarization curves.

### 3.1.3 Oxidation of Hydrazine

The electrode reactions of hydrazine in acid and basic solutions on smooth and platinized platinum have been examined. From analysis of the rest potentials and concentration relationships a rapid one electron exchange with a stable surface species has been postulated. The mechanism of oxidation occurs via a sequential system whereby hydrazinium radicals are the products of the initial oxidation.

The electrode reactions of carbon monoxide in acid solutions on smooth platinum electrodes have also been examined. The carbon monoxide is strongly bound to the metal surface and probably exists as a compound. Suppression of the reversible hydrogen reaction was observed in the presence of CO. Removal of the carbon monoxide film was performed as soon as oxide formation occurred indicating that the carbon monoxide is essentially electro-inactive and that the reaction is purely chemical with the metal oxide to form carbon dioxide. Electrochemical regeneration of the metal oxide forms the regenerative cycle.



The oxidation of methanol in acid does not proceed via carbon monoxide as an intermediate.

### 3.2 Chemisorption Studies

This work was principally focussed on the electrical properties of very thin evaporated metal films of silver, gold and nickel. It had been originally hoped that, following some suggestive results in the literature, we might be able to study the effect of adsorbed gases, in particular simple organic molecules and oxygen, on the conduction-band electrons in thin metal films with a view to elucidating the mechanism of the catalytic oxidation of small hydrocarbons.

We have been able to confirm that oxygen, nitrogen, hydrogen, ethylene and methane do indeed change the electrical resistance of thin films of these metals, but we were unable to find any systematic effects that could be used in a consistent analysis of the reaction mechanism. Thus with a given metal and a given gas the effect of exposing the metal film to gas may be either an increase or a decrease, large or small, in the electrical resistance of the film. Some of the effects are no doubt accidental and fortuitous. In working with evaporated metal films of thicknesses varying from a few hundred to a few thousand Angstrom units the difficulties are more formidable than had been anticipated. Admission of gas to the evacuated system in which the film had been evaporated in some cases caused a lifting of the metal film from the substrate on which it was evaporated, with consequent mechanical changes in the film and occasional actual rupture. In other cases the effects are real: they result from adsorption of the gas on the surface of the metal film -- mostly chemisorption -- and they reflect electron injection or abstraction from the metal film, depending on the type of chemical bonding involved, as found by earlier workers. Thus the original idea was sound, but proved to be experimentally too hard to utilize successfully.

The most serious difficulty is in reproducing the properties of the evaporated metal films. The sintering effects that occur after the original evaporation of the film are slow and very sensitive to thermal cycling. It was this difficulty more than anything else that led us finally to abandon this study, promising though the early results had been as a means of following the electronic bonding processes occurring in the catalytic oxidation of fuels.

Later parts of the work were directed to the catalytic oxidation of ethylene on much heavier catalysts, namely on coiled silver wires. The ethylene-oxygen reaction is a well studied one which was chosen as a means of evaluating a flow-system method for studying other fuels, and it emerged from this study that continuous monitoring of a flowing ethylene-oxygen gas stream passing over a silver catalyst wire by means of an inexpensive mass-spectrometric gas analyser is entirely feasible. Work did not proceed very far on this project, however, as it proved impossible to find post-doctoral personnel to carry out the detailed studies for other fuels.

The following papers and theses have been published or are now in preparation:

#### Papers

1. G. R. Bopp, D. M. Mason, "Electrode Kinetic Studies with a Translating Electrode", *Electrochem. Tech.* 2, 129-133, (1964).
2. G. R. Bopp, D. M. Mason, "Experimental Natural Convection Heat Transfer from Wires to Non-equilibrium Reacting System:  $\text{NO}_2\text{-NO-O}_2$ ", *Ind. and Eng. Fundamentals* 4, 222-224, (1965).
3. Szpak, P. Stonehart, Katan, "Electrode Reactions of  $\text{N}_2\text{H}_4$  in Aqueous Solutions", *Electrochim. Acta.* 10, (1965).

#### Theses

1. G. R. Bopp, Ph.D. Chemical Engineering, "Part I. Electrode Kinetics and Diffusion Using a Translating Electrode, Part

II, Natural Convection Heat Transfer in a Non-Equilibrium Chemical Reacting System", October 1963.

2. W. H. Smart, Ph.D., Chemical Engineering, "The Anodic Oxidation of Methanol on Single-Crystal and Polycrystalline Platinum", June, 1964.

Students who have received support from the contract are the following:

- A. Aldag, M.S., 1965
- G. R. Bopp, Ph.D., 1964
- W. H. Smart, Ph.D., 1964

## 4.0 THERMOELECTRIC ENERGY CONVERSION

### 4.1 Basic Materials Research

A determination of phase equilibria in the region of the Ag-Sb-Te system corresponding to  $\text{AgSbTe}_2$  has shown that material of this composition will normally exhibit a two phase microstructure. The phase which has previously been identified as  $\text{AgSbTe}_2$  was shown to be incongruently melting intermediate phase formed by a peritectic type reaction. The region of stability of this phase near the melting point extends from approximately 58 to 60 mole per cent  $\text{Sb}_2\text{Te}_3$  on the  $\text{Ag}_2\text{Te} - \text{Sb}_2\text{Te}_3$  section.

Hall coefficient and electrical resistivity measurements indicated the single phase material is degenerate with predominantly hole conduction. A hole mobility of  $7.8 \text{ cm}^2/\text{volt sec.}$  and a carrier concentration of  $1.4 \times 10^{20}/\text{cm}^3$  were calculated, assuming single carrier conduction only.

The intermediate phase can be indexed as a NaCl type structure with a lattice parameter of  $6.08 \text{ \AA}$  to  $6.09 \text{ \AA}$ . Density measurements indicate this corresponds to a vacancy concentration of approximately 2.5 per cent, which is taken to be indicative of a defect structure.

It is possible to retain single phase material in a meta-stable condition at room temperature, but prolonged annealing at an elevated temperature results in precipitation of  $\text{Sb}_2\text{Te}_3$ . The precipitation appears to be the result of retrograde solubility rather than a eutectoid decomposition.

### 4.2 Property Measurements at Elevated Temperatures

Instrumentation was developed to measure thermal diffusivity, Seebeck coefficient, and electrical resistivity for semiconductors from room temperature to about  $1000^\circ\text{C}$ . The thermal diffusivity was determined by placing the semiconductor sample in a furnace which contained a quartz window.

Irradiation of one side of the sample by a short duration flash lamp and measuring the temperature response of the back surface provided a means for calculating thermal diffusivity. Measurements on n-type and p-type PbTe showed a diffusivity between about  $1$  and  $2 \times 10^{-2} \text{ cm}^2/\text{sec}$  for temperatures up to  $500^\circ\text{C}$ .

For Seebeck coefficient and resistivity measurements, a furnace was constructed which provided a small temperature gradient as well as an elevated temperature. A modified four-point probe system using thermocouples as the inner probes permitted determination of Seebeck coefficient and resistivity nearly simultaneously. Data were obtained for PbTe for temperatures up to about  $600^\circ\text{C}$ .

#### 4.3 Transient Performance of Thermoelectric Generators

The problem of a thermoelectric generator initially at a uniform temperature which receives a step heat flux input at the hot junction was studied theoretically and experimentally. Because the current (for a constant external load) is a function of the junction temperature and the properties are temperature dependent, a numerical solution for temperature distribution and terminal voltage was found.

A single couple generator was constructed with an electric heater cemented to the hot junction bus bar. The cold junction was maintained at the initial temperature by a large heat sink. The experimental results provided confirmation of the theoretical results and showed that constant property calculations could be used (for PbTe) with adequate accuracy for prediction of temperatures but property variations must be considered in computing voltages.

The following papers and theses have been published:

##### Papers

1. R. A. Burmeister and D. A. Stevenson, "Concerning an Intermediate Phase in the Ag-Sb-Te System", Journal of Applied Physics, Vol. 34, No. 6, 1833, June 1963.

2. R. A. Burmeister and D. A. Stevenson, "Preparation and Electrical Properties of Silver Antimony Telluride", Transactions of the Metallurgical Society, AIME, Vol. 230, 329, March 1964.
3. C. B. Moyer and R. H. Eustis, "The Transient Performance of Thermoelectric Generators", Proceedings of the ASME International Conference on Energetics, University of Rochester, August 18-20, 1965.

#### Theses

Robert A. Burmeister, M.S., Material Science, Sept. 1962  
 "Phase Equilibria and Electrical Properties of a Ternary Intermediate Phase in the Silver-Antimony-Tellurium System". DMS Master's Report 62-7.

Carl B. Moyer, Ph.D., Mechanical Engineering, April, 1964,  
 "The Transient Response of Thermoelectric Generators".

Students who have received support from the contract are the following:

D. L. Bell	Engineer	1966
R. A. Burmeister	Ph.D.	1960
R. A. Reynolds	Ph.D.	1966
C. B. Moyer	Ph.D.	1964
L. H. Brim	Ph.D.	1966



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11. SUPPLEMENTARY NOTES (Citation)

12. SPONSORING MILITARY ACTIVITY

AF Office of Scientific Research (AFOSR)  
Office of Aerospace Research  
Washington, D. C. 20333

13. ABSTRACT

A brief summary is presented of the research conducted. Details of the work are reported in earlier reports. The scope of this program has included magneto-gasdynamic, electrochemical, and thermoelectric studies. In addition to a summary of the research work, 22 technical papers and ten theses, generating from this work, are listed. (U)

14.

KEY WORDS

LINK A

LINK B

LINK C

ROLE

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ROLE

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ROLE

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Direct Energy Conversion Devices  
Electrochemistry  
Energy Conversion  
Magnetogasdynamics  
Thermoelectricity

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